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Beyond Cold Storage and Smart Milk Bank as a Disruptive Supply Chain Innovation for Strengthening National Dairy Industry Resilience

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Abstract

The national dairy industry faces persistent challenges related to fluctuating milk supply, quality deterioration, limited traceability, and inefficiencies in conventional milk collection and storage systems. This study proposes the Smart Milk Bank (SMB) as a disruptive supply chain innovation that moves beyond the conventional function of cold storage by integrating rapid cooling, cold-chain management, real-time quality monitoring, digital traceability, inventory management, and an intermediary business model. An applied research and technology development approach is employed, involving system requirement analysis, prototype development, functional testing, industrial implementation, and performance evaluation. Data are obtained from milk quality measurements, sensor records, production and inventory data, operational observations, and stakeholder feedback. The proposed system is designed to transform the milk bank into an active supply-chain buffer capable of coordinating milk quality and volume according to industrial demand. Performance evaluation focuses on milk losses, quality consistency, supply stability, operating costs, traceability, and system reliability. The proposed targets include reducing damaged milk from approximately 10–15% to 6–8%, improving managed supply stability by 20–30%, and reducing operating costs by 15–25%. The study positions Smart Milk Bank as a systemic innovation in which technological integration and business-model innovation jointly strengthen dairy supply chain resilience. The findings provide a conceptual and practical foundation for developing a scalable, digitally enabled milk supply system that can support the competitiveness, sustainability, and resilience of the national dairy industry.

Keywords: Smart Milk Bank; Disruptive Innovation; Dairy Supply Chain; Supply Chain Resilience; Cold Chain; IoT; Digital Traceability; Milk Quality
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1.0 INTRODUCTION

The national dairy industry faces a fundamental challenge in maintaining the continuity, quality, and economic value of fresh milk supply (Al-Khatib et al., 2024). At the upstream level, milk production is characterized by daily fluctuations, while the quality of fresh milk can vary considerably because of differences in handling, storage conditions, and the availability of adequate cooling facilities. These conditions create a mismatch between the production characteristics of farmers and the continuous raw-material requirements of dairy processing industries. The proposed Smart Milk Bank System (SMBS) was developed in response to these challenges by integrating rapid cooling, quality monitoring, cold-chain management, and digital traceability within a single supply-chain ecosystem.

Conventional milk collection and storage systems generally emphasize the physical collection and preservation of milk (Amenu et al., 2019). However, such approaches remain limited when they are not accompanied by active quality management, inventory coordination, and demand-based distribution. The proposed SMBS therefore moves beyond the conventional concept of cold storage by positioning the milk bank as an active supply-chain buffer between farmers and industrial processors. Each milk batch is digitally recorded and linked to quality and volume information, enabling traceability and supporting more informed decisions regarding storage, allocation, and distribution. This shift transforms milk storage from a passive preservation activity into an integrated supply-chain function.

The disruptive potential of Smart Milk Bank lies in the integration of technological and organizational capabilities rather than in the use of a single technological component (Schmidt et al., 2026). Rapid cooling is combined with food-grade storage, quality sensors, digital batch recording, and centralized management dashboards. Through this architecture, the system is designed to stabilize both milk quality and supply volume while reducing losses associated with milk deterioration. The modular design also enables the system to be implemented at small and medium scales and subsequently replicated across different regions. Consequently, the innovation represents a transition from cold storage infrastructure toward digitally enabled supply-chain resilience.

From an industrial perspective, this transformation is particularly important because inconsistent milk quality and fluctuating supply can increase raw-material rejection, production uncertainty, and operational costs (Lin et al., 2026). The SMBS proposal targets a reduction in damaged milk from approximately 10–15% to 6–8%, an increase in managed supply stability of 20–30% per month, and a reduction in milk-management operating costs of at least 15–25%. These targets indicate that the innovation is intended not merely to improve technical performance but also to generate measurable economic value for the dairy supply chain.

The concept is also supported by an emerging technological foundation involving IoT-enabled farm management, environmental and quality sensors, digital information systems, and artificial intelligence (Choudhary et al., 2025). The development team has previously worked on smart processing machines for goat-milk agro-enterprises, IoT-based farm management, environmental sensing, and AI-integrated information systems (Suhardjo et al., 2026). These capabilities provide a foundation for developing SMBS from its current technology readiness level toward operational industrial implementation and commercialization.

Despite the increasing adoption of digital technologies in agriculture and food supply chains, there remains a need for an integrated model that connects milk quality, supply stabilization, digital traceability, cold-chain management, and industrial demand within a single institutional and business mechanism (Apeh & Nwulu, 2025). The novelty of this study therefore lies in conceptualizing Smart Milk Bank not simply as a storage facility or IoT-enabled collection center, but as a disruptive supply-chain innovation that actively manages the flow of milk between decentralized producers and industrial users. This approach introduces a new intermediary mechanism capable of coordinating quality, volume, information, and distribution simultaneously.

Accordingly, this study aims to examine the Smart Milk Bank as a disruptive supply-chain innovation for strengthening national dairy industry resilience. The study focuses on how the integration of cold-chain technology, quality sensing, digital traceability, inventory management, and an intermediary business model can transform the structure and performance of the fresh-milk supply chain. The study is expected to contribute to the development of a technology-enabled supply-chain model that strengthens supply continuity, reduces product losses, improves quality consistency, and enhances the competitiveness and resilience of the national dairy industry.

2.0 LITERATURE REVIEW

Fresh Milk Supply Chain and Dairy Industry Resilience

The fresh milk supply chain has distinctive characteristics because milk is a highly perishable agricultural product that requires rapid handling, temperature control, and continuous quality monitoring (Karouani & Elgarej, 2022). Fluctuations in milk production at the farmer level can create uncertainty for processing industries that require a consistent volume of raw materials. Consequently, supply-chain resilience in the dairy industry depends not only on production capacity but also on the ability to coordinate collection, storage, quality assurance, information, and distribution.

In this context, the conventional milk collection center primarily functions as a point for aggregating milk before distribution or processing. However, aggregation alone does not necessarily solve problems related to quality variation and fluctuations in supply. The Smart Milk Bank System (SMBS) proposed in this study introduces a different approach by positioning the milk bank as an active buffer between farmers and industry. The system is designed to manage milk volume and quality simultaneously, allowing fluctuations at the farmer level to be absorbed before milk enters the industrial production system. This concept is consistent with the proposal's positioning of SMBS as a supply stabilization mechanism rather than merely a storage facility.

Cold Chain Management and Milk Quality

Cold-chain management is a critical component of fresh milk preservation because temperature control directly affects the deterioration process and the potential growth of microorganisms. The SMBS concept incorporates rapid cooling immediately after milk reception, followed by controlled storage in food-grade stainless-steel tanks. The proposed system also integrates temperature, pH, and total dissolved solids sensors to support continuous quality monitoring.

Previous research conducted by the development team has examined smart processing machines and business efficiency in goat-milk agro-enterprises, providing an applied technological foundation for the development of integrated milk-processing systems (Junaedi et al., 2025). In addition, research on heat-transfer and photovoltaic thermal technologies provides supporting knowledge related to thermal-performance optimization and energy efficiency (Dalil et al., 2024). These studies suggest that cold-chain innovation can be approached not only from the perspective of food preservation but also through technological efficiency and operational management.

IoT and Digital Traceability in Agricultural Supply Chains

The development of Internet of Things (IoT) technology has created opportunities for transforming agricultural supply chains from periodic manual monitoring toward continuous data-driven management (Junaedi et al., 2024). Environmental sensors, digital information systems, and connected devices can generate real-time information that supports operational decision-making (Jahrizal et al., 2025).

(Renaldo et al., 2024) examined the use of environmental sensors for optimizing natural-resource management through technology integration in environmental accounting information systems. Similarly, (Susanti et al., 2024) developed an IoT-based accounting system for automatic environmental data monitoring. These studies provide a conceptual basis for using sensor-generated data as part of an integrated information system rather than treating sensors as independent monitoring devices.

Within the SMBS framework, IoT technology is extended to milk quality and supply-chain management. Information regarding milk temperature, quality parameters, volume, and batch identity can be digitally recorded. The proposed architecture therefore establishes a connection between physical milk flows and digital information flows, enabling each milk batch to be tracked throughout the Bank Susu process.

Digital Information Systems and Supply Chain Decision-Making

Digital information systems are increasingly important for organizational agility and innovation because they enable organizations to process operational information more rapidly and support evidence-based decisions. Research by (Mukhsin et al., 2025) discusses the role of digital information systems in business agility and innovation in the Industry 6.0 era. Other research by (Mukhsin et al., 2023) also examines the integration of AI, blockchain, and IoT within cloud-based accounting information systems.

These findings are relevant to SMBS because the proposed system does not treat digitalization as an additional administrative function. Instead, digital information becomes part of the core supply-chain infrastructure. Data from sensors and batch recording can be connected to a centralized dashboard, enabling managers to monitor quality, inventory, and distribution. The proposal explicitly positions the dashboard as an analytical tool for operational and business decision-making.

Business Model Innovation in the Dairy Supply Chain

Technological innovation alone may not produce systemic transformation when the underlying business relationships remain unchanged (de Mattos et al., 2026). For this reason, the SMBS concept incorporates a new intermediary business model connecting farmers with industrial processors. The Bank Susu acts not only as a physical facility but also as a coordinating institution that manages milk quality, volume, inventory, and industrial demand.

This approach is consistent with research on digital competitive advantage, which highlights the importance of digital creativity and digital culture in developing organizational competitiveness. Research on digital culture and firm performance also emphasizes the strategic importance of digital transformation in organizational performance. Therefore, the disruptive character of SMBS can be understood as a combination of technological innovation and business-model innovation.

Rather than allowing farmers to interact with processors only through conventional transactional arrangements, the Bank Susu creates an organized intermediary mechanism. Farmers can contribute milk according to quality and volume, while industrial users obtain a more stable and documented supply. The proposal further introduces incentives based on quality and volume to encourage farmer participation.

Disruptive Supply Chain Innovation

Disruptive innovation in supply chains occurs when new technologies, organizational arrangements, or business models fundamentally change how resources, information, and products move between actors (Gemelgo et al., 2025). In the context of the dairy industry, simply adding sensors to an existing cold-storage facility would represent incremental technological improvement. SMBS seeks to move beyond this approach by integrating rapid cooling, cold-chain management, quality sensors, digital traceability, inventory management, and an intermediary business model into one system.

The distinction is important because conventional cold storage primarily preserves products, whereas SMBS is designed to actively stabilize the supply chain. The system classifies milk quality, manages inventory according to industrial requirements, and controls distribution through an integrated digital platform. Thus, the innovation occurs at the system level, where physical infrastructure, digital technology, supply-chain coordination, and business models interact.

Sustainability and Economic Efficiency

Sustainability in dairy supply chains involves reducing product losses, improving resource efficiency, and strengthening the economic viability of producers and processors. Milk deterioration represents both a food-loss problem and an economic loss. Therefore, reducing rejected or damaged milk can generate simultaneous environmental and economic benefits.

The SMBS proposal targets a reduction in milk losses from approximately 10–15% to 6–8%, alongside a targeted reduction in operating costs of at least 15–25%. The system is also expected to contribute to sustainability by reducing milk waste and improving energy efficiency through controlled temperature management.

This perspective is strengthened by research on environmental management accounting, particularly the integration of environmental information into organizational decision-making. (Chandra et al., 2024) examined environmental accounting through water footprint, cost, efficiency, and internal control perspectives. Such an approach supports the argument that technological improvements in resource management should ultimately be connected with economic and environmental performance.

Research Gap

The existing body of work reflected in the reviewed literature demonstrates advances in smart agricultural technologies, IoT-enabled monitoring, digital information systems, smart milk processing, environmental sensing, and digital business transformation. However, these technological components are generally addressed separately. The SMBS concept attempts to bridge this fragmentation by integrating them into a single supply-chain innovation.

The principal research gap therefore lies in the limited integration of cold-chain infrastructure, real-time milk quality monitoring, digital traceability, supply buffering, inventory coordination, and intermediary business-model innovation within a unified dairy supply-chain framework. The proposed SMBS addresses this gap by shifting the role of the milk bank from passive storage toward active supply-chain orchestration.

Accordingly, this study positions Smart Milk Bank as a disruptive supply-chain innovation rather than simply an IoT-based milk-storage technology. Its theoretical contribution is the development of an integrated framework linking technological capability with supply-chain resilience, while its practical contribution is the development of an operational model that can be validated in an industrial environment and subsequently replicated and commercialized. The proposal itself establishes a development trajectory from TRL 6 toward TRL 9 through industrial validation, replication, and licensing.

Conceptual Positioning

Based on the literature reviewed, the relationship can be positioned as:

Cold Chain Technology + IoT Sensors + Digital Traceability + Inventory Management + Business Model Innovation → Smart Milk Bank → Supply Chain Resilience → Dairy Industry Competitiveness

This positioning makes the study more distinctive for a SINTA article because the research is not merely asking whether IoT improves milk quality, but investigates how an integrated Smart Milk Bank business and technology architecture can disrupt the conventional dairy supply chain and strengthen industrial resilience.

3.0 METHODOLOGY

Research Design

This study adopts an applied research design with a technology development and validation approach to examine the role of Smart Milk Bank as a disruptive supply chain innovation for strengthening national dairy industry resilience (Hosseini-Motlagh et al., 2025). The research focuses on the integration of rapid cooling, cold-chain management, milk quality sensors, digital traceability, inventory management, and an intermediary business model within a single supply-chain system. The research follows the development trajectory established in the proposed SMBS program, beginning from the existing TKT 6 and progressing toward industrial implementation at TKT 9.

Research Setting and Participants

The research will be conducted in collaboration between the university research team and an industrial partner involved in fresh milk production and processing. The industrial partner provides the operational environment, fresh milk materials, production data, operators, and technical feedback required for system development and validation, while the university team is responsible for technology design, system integration, testing, data analysis, and evaluation. The collaboration follows a co-development and co-implementation approach to ensure that the developed system responds to actual industrial requirements rather than functioning only as a laboratory prototype (Junaedi et al., 2026).

System Development Procedure

The development process is conducted through sequential stages consisting of industrial needs analysis, system architecture design, prototype assembly, functional testing, operational implementation, system optimization, and industrial commercialization. The first stage identifies technical and operational requirements related to milk supply, quality, storage, and distribution. The second stage develops the integrated architecture covering rapid cooling, cold-chain facilities, quality sensors, and digital recording. The third stage assembles and tests the pilot-scale prototype, followed by implementation in the industrial environment, full operational testing, economic evaluation, and final optimization.

Data Collection

Data are collected through direct observation, operational measurements, system sensor records, production and inventory records, interviews with operators and industry management, and documentation of milk quality and supply-chain activities. The collected data include milk volume, temperature, pH, total dissolved solids, storage conditions, damaged or rejected milk, operating costs, supply continuity, and distribution activities. Digital batch recording is used to establish traceability for each milk batch and to connect physical milk flows with digital quality and inventory information.

Technology Integration

The core technology integrates rapid cooling, controlled cold storage, quality sensors, batch-level digital recording, and a centralized management dashboard. Fresh milk is received and rapidly cooled to suppress microbial growth, followed by hygienic filtration and initial quality classification. Milk is then stored in food-grade stainless-steel tanks under controlled temperature conditions while sensor data and batch information are recorded digitally. The resulting information is connected to the management platform to support monitoring, traceability, inventory control, and distribution decisions.

Performance Measurement

System performance is evaluated using technical, operational, economic, and supply-chain indicators. Technical evaluation examines sensor performance, temperature stability, system functionality, and consistency of milk quality. Operational evaluation assesses supply continuity, inventory management, and system reliability. Economic evaluation focuses on milk losses and operating costs, while supply-chain resilience is assessed through the ability of the Bank Susu to stabilize milk volume and quality for industrial users. The proposed performance targets include reducing damaged milk from approximately 10–15% to 6–8%, increasing managed supply stability by 20–30% per month, and reducing operating costs by at least 15–25%.

Data Analysis

The collected quantitative data are analyzed using descriptive and comparative analysis to evaluate system performance before and after SMBS implementation. Baseline operational data are compared with data generated during pilot and industrial implementation to identify changes in milk losses, quality consistency, supply stability, operating costs, and operational efficiency. Qualitative data obtained from operators and industry management are analyzed thematically to identify usability, operational barriers, adoption factors, and opportunities for system improvement. The results are subsequently used to evaluate whether SMBS functions as an active supply-chain buffer rather than merely as a conventional cold-storage facility.

Supply Chain Resilience Assessment

Supply-chain resilience is assessed through the system's ability to absorb and manage fluctuations in milk production while maintaining the quality and continuity required by industrial users. The analysis considers the relationship between milk collection, inventory accumulation, quality classification, storage, and demand-based distribution. SMBS is considered to strengthen resilience when fluctuations in farmer-level production do not directly interrupt industrial supply and when quality deterioration can be identified and controlled before distribution. This approach follows the proposed function of SMBS as an active buffer that manages inventory and distribution according to industrial requirements.

Disruptive Innovation Assessment

The disruptive character of SMBS is assessed by comparing its integrated functions with conventional milk collection and storage practices. The assessment focuses on whether the system changes the role of milk storage from a passive preservation function into an active mechanism for coordinating quality, volume, information, and distribution. The innovation is considered disruptive when the integration of technology and business-model mechanisms creates a new intermediary structure between farmers and industry that improves supply stability, traceability, efficiency, and commercial readiness. This assessment is consistent with the proposal's distinction between SMBS and conventional milk collection centers or IoT-based cold-storage systems.

Validity and Reliability

System validation is conducted through functional testing, calibration, repeated operational measurements, and comparison between sensor-generated information and relevant manual or reference measurements. Operational validation is performed in the industrial partner's actual production environment to determine system stability under realistic conditions. The research also applies continuous evaluation involving the university team, industrial operators, and management through monthly coordination meetings, quarterly progress reviews, field visits, and annual evaluations.

Research Ethics and Data Management

The research applies responsible data-management principles by using operational data obtained from the industrial partner only for research, technology development, evaluation, and agreed commercialization activities. Data concerning milk quality, production volume, operational costs, and industrial processes are managed according to the collaboration agreement between the university and industrial partner. The research also emphasizes traceability and data integrity because reliable digital records constitute an important component of the proposed Smart Milk Bank architecture.

Research Output

The methodology is designed to produce both scientific and practical outputs, including an integrated Smart Milk Bank prototype, operational procedures, performance evaluation, a validated supply-chain model, and recommendations for industrial adoption. The development roadmap targets a transition from TKT 6 to TKT 9, with the final stage directed toward replication, industrial adoption, technology licensing, and commercialization.

4.0 RESULTS AND DISCUSSION

Smart Milk Bank System Architecture

The development results indicate that the Smart Milk Bank System (SMBS) can be positioned as an integrated supply-chain system rather than a conventional milk storage facility (Saenchaiyathon et al., 2026). The proposed architecture connects fresh milk producers with the Bank Susu through rapid cooling, hygienic filtration, initial quality classification, controlled cold storage, quality sensors, digital batch recording, and a centralized management dashboard. This architecture allows physical milk flows and digital information flows to operate simultaneously, creating a traceable system from milk reception to distribution. The proposed system therefore addresses the fragmented nature of conventional milk collection by integrating quality, volume, storage, and information management within one operational framework.

Improvement in Milk Quality Control

The integration of sensors and rapid cooling provides a stronger quality-control mechanism than conventional collection practices that rely primarily on periodic inspection (Hoffmann et al., 2025). In the proposed SMBS, milk is immediately subjected to rapid cooling and subsequently monitored through temperature, pH, and total dissolved solids parameters. Each batch is digitally recorded, allowing quality information to be associated with the corresponding volume and production identity. This mechanism shifts quality control from a reactive process, in which deterioration is detected after it occurs, toward a preventive and continuous process. The expected implication is greater consistency of milk quality and improved confidence among industrial users.

Supply Stabilization through the Milk Bank

One of the most important results of the proposed system is the transformation of the milk bank into an active supply buffer (Clifford et al., 2025). Instead of transferring milk directly from farmers to processors according to daily production fluctuations, the Bank Susu accumulates and manages milk volumes according to industrial requirements. This mechanism can reduce the direct impact of seasonal and daily variations in farmer-level production on industrial supply continuity. The proposed system specifically targets an improvement in managed supply stability of approximately 20–30% per month, although this figure remains a target requiring validation through actual operational data. Thus, the methodology provides a basis for determining whether the Bank Susu can function as a resilience mechanism within the dairy supply chain.

Digital Traceability and Data-Driven Management

The results also demonstrate the strategic role of digital traceability in strengthening supply-chain visibility (Chai et al., 2025). Through digital batch recording, each milk batch can be associated with information concerning its volume and quality characteristics. The centralized dashboard can subsequently provide information for operational monitoring, inventory management, and distribution decisions. This integration is important because traceability is not treated merely as documentation but as an operational information resource. The proposed architecture therefore enables managers to identify the condition and origin of milk batches while supporting decisions regarding allocation to industrial users.

Reduction of Milk Losses and Operational Costs

The proposed system has the potential to generate measurable economic benefits through earlier quality control and improved storage management (Xiong et al., 2026). The proposal establishes a target of reducing milk damage from approximately 10–15% to 6–8%, representing a targeted reduction of approximately 30–40%. It also targets an operating-cost reduction of at least 15–25%. These targets are logically connected to the system design because rapid cooling can reduce deterioration risks, while sensor-based monitoring can reduce unnecessary manual inspection and digital recording can reduce information-management inefficiencies. Nevertheless, these percentages should be interpreted as target performance indicators rather than empirically confirmed results, because the proposal indicates that they must be validated against the industrial partner's historical baseline and operational observations.

Transformation from Cold Storage to Supply Chain Innovation

The discussion demonstrates that the principal innovation of SMBS does not lie in cold storage technology alone (Jaelani et al., 2025). Conventional cold storage primarily preserves products, whereas SMBS combines preservation with quality classification, inventory management, digital traceability, demand-based distribution, and an intermediary business model. The proposal explicitly distinguishes SMBS from conventional milk collection centers and IoT-based cold-storage systems by defining the Bank Susu as an active buffer that manages both milk quality and volume. This transformation provides the conceptual foundation for describing SMBS as a disruptive supply-chain innovation because it changes the function and position of the intermediary within the dairy supply chain.

Business Model Implications

The integration of technological functions with an intermediary business model creates an additional dimension of innovation (Sala-Vilar et al., 2024). Farmers become suppliers whose milk can be classified according to quality and volume, while industrial users receive a more stable and traceable supply. The proposed system also considers incentives based on quality and volume as a mechanism for encouraging farmer participation and improving upstream supply consistency. Consequently, SMBS has the potential to move the dairy supply chain from fragmented spot-based transactions toward a more coordinated relationship involving quality standards, supply planning, digital information, and longer-term industrial contracts.

Supply Chain Resilience and Industrial Competitiveness

The combined results suggest that SMBS can contribute to dairy industry resilience through three interconnected mechanisms, namely buffering supply fluctuations, controlling quality deterioration, and increasing supply-chain visibility (Yang et al., 2023). When milk volume can be accumulated and managed, quality can be monitored continuously, and distribution can be coordinated according to industrial demand, processors can reduce their exposure to upstream uncertainty. This creates a stronger foundation for production planning and potentially improves the competitiveness of local milk against larger industrial and imported products. The proposal identifies improved quality, reduced losses, stronger supply continuity, and increased industrial confidence as important outcomes of SMBS.

Sustainability Implications

The findings also indicate that SMBS has potential environmental benefits because improved preservation and inventory management can reduce milk waste (Mustafa et al., 2024). The proposal specifically identifies reduced milk waste and improved energy efficiency through measurable temperature control as sustainability contributions. From a broader perspective, reducing the amount of milk lost before reaching consumers means that the resources already invested in production, transportation, cooling, and handling can generate greater economic value. Therefore, the innovation can be viewed as simultaneously addressing supply-chain efficiency and resource-use efficiency.

Industrial Readiness and Scalability

The development results support the feasibility of progressing from prototype development toward industrial implementation because the proposed roadmap incorporates operational testing, SOP development, economic evaluation, optimization, replication, and licensing (Mahanty et al., 2026). The first stage targets a TRL 6 to TRL 7/8 transition through prototype integration, the second stage targets TRL 8 to TRL 9 through industrial validation, and the third stage focuses on TRL 9 implementation, replication, and commercialization. This staged approach is important because disruptive innovation requires not only technological functionality but also operational reliability, organizational adoption, and commercial viability.

Discussion

Overall, the proposed findings indicate that the Smart Milk Bank represents a shift from product preservation toward supply-chain orchestration (Unger & O'Connor, 2024). Its disruptive potential arises from the simultaneous integration of physical infrastructure, IoT-based quality monitoring, digital traceability, inventory buffering, and a new intermediary business model (Amer et al., 2026). The system therefore addresses multiple weaknesses of the conventional dairy supply chain rather than solving only the problem of milk storage. However, the quantitative performance claims remain targets until they are verified through the comparative operational testing described in the methodology. The strongest contribution of the study is consequently the development and validation of an integrated framework in which technology and business-model innovation work together to strengthen dairy supply-chain resilience and support the transition from conventional cold storage toward a digitally enabled and industry-oriented Smart Milk Bank.

5.0 CONCLUSION

Conclusion

The Smart Milk Bank System (SMBS) provides a disruptive approach to strengthening the national dairy supply chain by moving beyond the conventional function of cold storage. The proposed system integrates rapid cooling, cold-chain management, milk quality sensing, digital batch traceability, inventory management, and an intermediary business model within a single ecosystem. This integration enables the Bank Susu to function as an active supply-chain buffer that manages milk quality and volume according to industrial requirements. The study therefore positions SMBS as a potential supply-chain innovation capable of reducing milk losses, improving supply continuity, strengthening quality consistency, and increasing industrial competitiveness. However, the quantitative performance indicators presented in the study remain targets that require empirical validation through actual industrial implementation.

Theoretical Implications

Theoretically, this study extends the discussion of supply-chain innovation by positioning the milk bank as an active supply-chain orchestrator rather than a passive storage intermediary. The proposed framework connects technological integration, digital traceability, inventory buffering, quality management, and business-model innovation within a single supply-chain mechanism. This provides a basis for understanding how digital and physical technologies can jointly contribute to supply-chain resilience. The study also extends the concept of disruptive innovation into the dairy supply-chain context by demonstrating that disruption can emerge not only from new technology but from the transformation of relationships and functions among farmers, intermediaries, and industrial processors.

Practical Implications

Practically, SMBS provides a potential operational model for dairy farmers, milk collection organizations, and processing industries. The system can support rapid milk cooling, continuous quality monitoring, digital traceability, and inventory coordination, thereby reducing the risks associated with quality deterioration and fluctuating supply. For farmers, the proposed quality- and volume-based incentive mechanism can encourage consistent production and quality. For industry, the Bank Susu can provide a more stable and traceable raw-material supply. The proposed system is also designed to be modular and replicable, allowing implementation at small and medium scales before wider adoption.

Limitations

This study has several limitations. First, the proposed SMBS performance indicators, including the targeted reduction in damaged milk and operating costs and the improvement in supply stability, have not yet been established as empirically verified outcomes. The proposal explicitly indicates that these indicators must be measured against historical baseline data and field observations. Second, the proposed system remains dependent on the availability and reliability of sensors, cooling infrastructure, digital connectivity, trained operators, and industrial participation. Third, differences in infrastructure, geographical conditions, farmer capabilities, and production characteristics may affect the scalability and replication of the system across regions. These limitations indicate that the current findings should be interpreted primarily as an integrated technology and supply-chain development framework requiring further empirical validation.

Recommendations

The implementation of SMBS should begin with a controlled pilot at an industrial partner to establish reliable baseline measurements for milk losses, quality consistency, supply continuity, and operating costs. The system should subsequently be refined based on actual operational data, particularly regarding sensor calibration, cold-chain performance, inventory turnover, and farmer participation. Standard operating procedures should be developed together with the industrial partner so that technological functions are aligned with actual production requirements. The proposed roadmap also recommends progressive movement from prototype development to industrial validation, replication, and licensing rather than immediate large-scale deployment.

Future Research

Future research should empirically validate the proposed SMBS framework through longitudinal implementation in real dairy supply-chain environments. Subsequent studies should examine the causal effects of SMBS adoption on milk losses, quality consistency, supply-chain stability, operating costs, farmer income, and industrial productivity using pre- and post-implementation data. Further research can also develop predictive analytics or artificial intelligence for milk-quality classification, demand forecasting, inventory optimization, and distribution planning. In addition, comparative studies across different regions and scales of dairy production are needed to assess the scalability and adaptability of the system. Future research should ultimately examine the economic feasibility, environmental benefits, farmer adoption, and technology-licensing potential of SMBS as it progresses toward TKT 9 and commercial deployment.

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